DSN/Flight Project
Interface Design

TRK-30, Rev. E
DSN Tracking System, Ranging
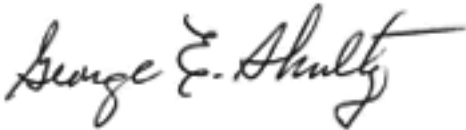
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1.   Introduction

1.1   Purpose

This module describes the capabilities and provides the performance parameters of the Deep Space Network (DSN) ranging equipment for the 70-m, the 34-m High Efficiency (HEF), the 34-m Beam Waveguide (BWG), the 34-m Standard (STD), and the 26-m subnets.

1.2   Scope

The discussion in this module is limited to those parameters and operational considerations that are independent of the particular antenna being used to provide the telecommunications link. For antenna-dependent parameters, refer to the appropriate telecommunications interface (TCI) module of this handbook.

2.   General Information

The Deep Space Network (DSN) ranging equipment uses a sequentially binary-coded technique to measure the round trip light time (RTLT) between a Deep Space Station (DSS) and the spacecraft. The measurement is made by the Sequential Ranging Assembly (SRA). The SRA generates a sequence of square-wave frequencies which are modulated onto the uplink carrier. This signal is received by the spacecraft on-board transponder, demodulated, filtered and remodulated onto the downlink carrier. The SRA correlates the demodulated downlink signal with a Doppler-modified replica of the transmitted codes which were sent to the spacecraft approximately one RTLT earlier. The RTLT or 2-way range is then determined by measuring the phase difference between the received code and the Doppler-modified transmitted code.

The next paragraph gives a description of the DSN ranging system. The parameters to be specified for ranging operations are explained in Paragraph 2.2. Paragraph 2.3 presents the process of range measurement that includes the evaluation of RTLT, ranging power to noise ratio (P_r/N_O), Figure of Merit (FOM), and Differential Range Versus Integrated Doppler (DRVID). The relationship of downlink ranging power over total power is given in Paragraph 2.4. Paragraph 2.5 provides the corrections required to determine the actual range to a spacecraft. Error contributions of the ground system are specified in the last paragraph.

2.1 *System Description*

The DSN ranging system is basically formed by four groups of equipment. The uplink portion has an exciter and a transmitter. The downlink elements include a low noise amplifier (LNA) and a receiver. The front-end portion consists of the microwave components and the antenna. The SRA and Metric Data Assembly (MDA) form the tracking subsystem, which performs range measurement, formats radiometric data, and sends the data to the Navigation subsystem (NAV). The NAV processes and provides the data to projects. Figure 1 below describes the DSN ranging system.
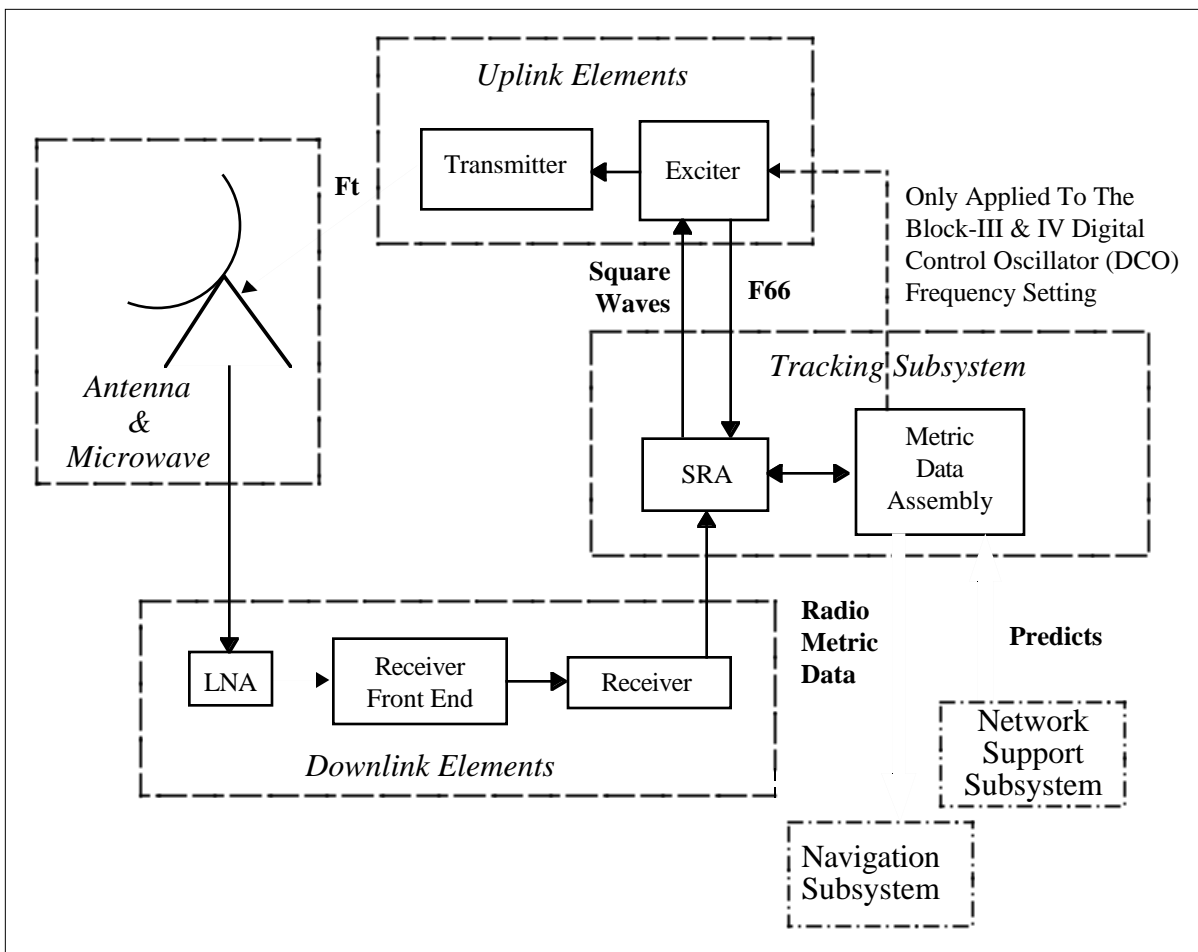
Figure 1. The DSN Ranging System

On the uplink side as shown in Figure 1, the SRA has two hardware interfaces with the exciter. The first is a coaxial interface which provides a reference frequency (F66, approximately 63 - 66 MHz) from the exciter to the SRA. The second interface is also a coaxial cable which supplies the square-wave signal to the modulator in the exciter. Frequency relationship for these two signals are further explained in Paragraph 2.2.2 below.

The DSN currently has both analog and digital closed-loop receivers. For an analog receiver (MFR, Block-III or Block-IV), two coaxial cables are used to pass a 10-MHz I.F. and a 5-MHz Doppler reference to each of the two SRA channels. (The SRA has two channels. Channel 1 is normally used to process S-band data and channel 2 is used to process X-band Data.) The 10-MHz I.F. contains ranging tones which are demodulated and correlated in the SRA. The 5-MHz reference is used for Doppler rate aiding during range measurements.

In the Block-V receiver (BVR) implementation, demodulation of the ranging code is done within the BVR. The two ranging basebands (normally one for S-band and one for X-band) are sent to the SRA as digital data through an optical fiber interface. In addition, the BVR provides two analog signals, the Doppler clock and the bias frequency, through coaxial cables to the SRA. The Doppler clock is sometimes referred to as the 1 MHz signal and the bias frequency is sometimes referred to as the 65 MHz signal.

The Doppler clock, F_{DC}, is computed from the received frequency as follows:

$$F_{DC} = \frac{S_e}{K} \cdot f_r - f_b$$

where:

f_r =   received carrier frequency

K   =   spacecraft turn around ratio:

         240/221 for S-up/S-down

         880/221 for S-up/X-down

         240/749 for X-up/S-down

         880/749 for X-up/X-down

S_e =   1/32 for S-up

         11/1200 for X-up using 34-m HEF X-band exciter

         221/(749 x 32) for X-up using Block-V exciter (BVE)

f_b =   bias frequency given by:

$$f_b = \frac{160}{256} \cdot \text{trunc}\left[\frac{256}{160} \cdot \left(0.5 + \frac{S_e}{K} - 1.0\right)\right], \quad \text{(MHz)}$$

in which trunc[*] is the truncation function.

This bias frequency only has six possible values: 62.5 MHz, 63.125 MHz, 63.75 MHz, 64.375 MHz, 65.0 MHz, and 65.625 MHz.

2.2 *Parameters Specified for Ranging Operations*

This following paragraphs present the parameters that are required in ranging operations.

2.2.1 *Transmit Time and Receive Time*

The SRA needs a transmit time (XMIT) and a receive time (T_O) so that the code sequence can be sent and received for measuring the phase shifted through round-trip-time delay. When a XMIT and an approximate RTLT are specified, the SRA automatically calculates the receive time T_O by adding the two given quantities: $T_O = XMIT + RTLT$. This T_O is also called the start time of the correlation process for the code sequence. These time quantities are specified and evaluated in integer seconds.

2.2.2 *Clocks and Components*

A range measurement begins with the highest frequency code followed by subsequent codes each having a frequency exactly half of the previous one. The first code in the sequence is called the clock component and determines the resolution of the measurement. The lower frequency codes that follow are used to resolve the ambiguity (uncertainty) of the a priori range estimate.

Table 1 shows the clocks and components used in ranging operations. A total of 22 code components are available. They are component numbers 3 through 24 as shown in the Table. The first 8 components (numbered 3 through 10) are called the clock components or simply clocks. The approximate ambiguity resolving capability of a component is listed in the Table for reference. The approximate frequencies and periods of the codes are also shown.

The frequency (F_C) in the second column is computed by the relationship:

$$F_C = \frac{F66}{2^{2+n}}$$

where:

n is an integer from 3 to 24 which represents a code component or a component number.

The value of F66 used to produce Table 1 is 66 MHz. In ranging operations, this frequency varies depending upon the transmitting (uplink) carrier frequency. F66 is denoted by F66s, F66x, or F66xv for a reference frequency derived from a S-band, X-band Block III, or X-band Block-V exciter respectively. It can be expressed in terms of the uplink frequency as follows:

S-band uplink:

$$F66s = \frac{1}{32} \times Fts$$

Change 1: January 15, 1997

Table 1. Range Code Resolving Capability

Component Number	Approximate Frequency (Hertz)	Approximate Period (Seconds)	Approximate Ambiguity Resolving Capability (km)
3*	2.06E+06	4.85E-07	7.27E-02
4*	1.03E+06	9.70E-07	1.45E-01
5*	5.16E+05	1.94E-06	2.91E-01
6*	2.58E+05	3.88E-06	5.81E-01
7*	1.29E+05	7.76E-06	1.16E+00
8*	6.45E+04	1.55E-05	2.33E+00
9*	3.22E+04	3.10E-05	4.65E+00
10*	1.61E+04	6.21E-05	9.30E+00
11	8.06E+03	1.24E-04	1.86E+01
12	4.03E+03	2.48E-04	3.72E+01
13	2.01E+03	4.96E-04	7.44E+01
14	1.01E+03	9.93E-04	1.49E+02
15	5.04E+02	1.99E-03	2.98E+02
16	2.52E+02	3.97E-03	5.95E+02
17	1.26E+02	7.94E-03	1.19E+03
18	6.29E+01	1.59E-02	2.38E+03
19	3.15E+01	3.18E-02	4.76E+03
20	1.57E+01	6.36E-02	9.53E+03
21	7.87E+00	1.27E-01	1.91E+04
22	3.93E+00	2.54E-01	3.81E+04
23	1.97E+00	5.08E-01	7.62E+04
24	9.83E-01	1.02E+00	1.52E+05
* These are the 8 available clocks			

X-band uplink using the Block-III exciter:

$$F66x = \frac{11}{1200} \times Ftx$$

X-band uplink using the Block-V exciter:

$$F66xv = \frac{221}{749 \times 32} \times Ftx$$

where, Fts and Ftx are the S- and X-band transmitting (uplink) frequencies.

The third column (approximate period) shows the periods of the corresponding frequencies in the second column. The fourth column (ambiguity resolving capability) lists the products of the periods and the speed of light (299792.5 Km/s).

Note that clock 3 (the 2-MHz clock) is available but it is not used at this time. This is because all ranging modulators of the DSN exciters and the ranging channel for most spacecraft have a one-sided bandwidth less than or equal to 2 MHz.

Depending on the uncertainty of the range estimate, a flight project determines the number of components needed for ranging operations. An example in choosing the clock and components is given as follows:

Example: Suppose the spacecraft is known to be at a 10-minute RTLT from Earth to within ±100,000 Km. If it is desired to resolve the ambiguity to about 40,000 Km, and if the resolution of measurement needed is 150 m, then components 4 through 22 should be defined for ranging. In other words, clock 4 (about 1 MHz) is used with the subsequent 18 components (5 through 22).

2.2.3   *Square-Wave and Sine-Wave Ranging*

The SRA may process the received codes in two ranging modes. They are referred to as square-wave and sine-wave operations.

For square-wave operation, the SRA processes all harmonics of the received codes. For sine-wave operation, only the fundamental (the first harmonic) is processed. The difference can be summarized by:

Square-wave operation:	*transmit* **square waves**
	receive **square waves**
Sine-wave operation:	*transmit* **square waves**
	receive **sine waves**

Ranging with the 1-MHz clock is a special case due to the limited ranging bandwidths of most spacecraft and DSN ranging modulators. Because the downlink square waves are heavily filtered, they are treated as sine waves regardless of which ranging operation is specified.

2.2.4   *Integration Times*

Three integration times must be specified for ranging operations. They are: T1 for clock integration, T2 for each component integration, and T3 for DRVID measurement(s).

2.2.4.1   *T1*. T1 is the total time used to integrate the correlation samples for the clock. This integration time is a function of the clock frequency (F_c in Hertz), the desired variance (σ^2 in seconds^2) of RTLT measurements, and the ranging signal to noise spectral density (Pr/No in Hz). The relationships are given as follows:

Sine-wave operation:

$$T1 = \frac{1}{56} \times \frac{1}{F_c^2} \times \frac{1}{\sigma^2} \times \frac{1}{P_r/N_0}, \ \ (\text{seconds})$$

Square-wave operation:

$$T1 = \frac{8}{343} \times \frac{1}{F_c^2} \times \frac{1}{\sigma^2} \times \frac{1}{P_r/N_0}, \ \ (\text{seconds})$$

The above equations can be rewritten in terms of the uncertainty (σ) of measurement in meters. Dividing σ by 150000000 m/s (one-half the speed of light) yields the following one-way range uncertainty expressions:

Sine-wave operation:

$$\sigma = \sqrt{\frac{402}{F_c^2 \times T1 \times P_r/N_0}}, \ \ (\text{meters})$$

Square-wave operation:

$$\sigma = \sqrt{\frac{523}{F_c^2 \times T1 \times P_r/N_0}}, \ \ (\text{meters})$$

where:

F_c = the clock frequency in unit MHz

T1 = the clock integration time in seconds

P_r/N_0 = numeric value of the ranging signal to noise spectral density in Hz (not dB-Hz)

Note: The uncertainty (σ) here is only due to thermal noise. Other errors must be added to this to get the total uncertainty (see Paragraph 2.6).

For convenience, the above equations have been plotted in Figures 2 through 14 for the seven clocks (1 MHz to 15.625 KHz) used in the DSN. For a desired σ, the user may easily find the proper integration time, T1, on the graphs in terms of an estimated P_r/N_0 (in dB-Hz). Note that both axes (T1 and P_r/N_0) on these graphs are in logarithmic scale. Also, the vertical heavy line marked at -10 dB-Hz is a recommendation that users perform ranging link analysis based on P_r/N_0 at or above the -10 dB-Hz level. In theory, there should not be a lower limit for P_r/N_0 in measuring range as long as the receiver is in lock during the time of measurement. The limit is really tied to a combination of integration times (cycle time) and the minimum number of range points needed by the project. See Cycle Time in Paragraph 2.2.4.4 for further detail.
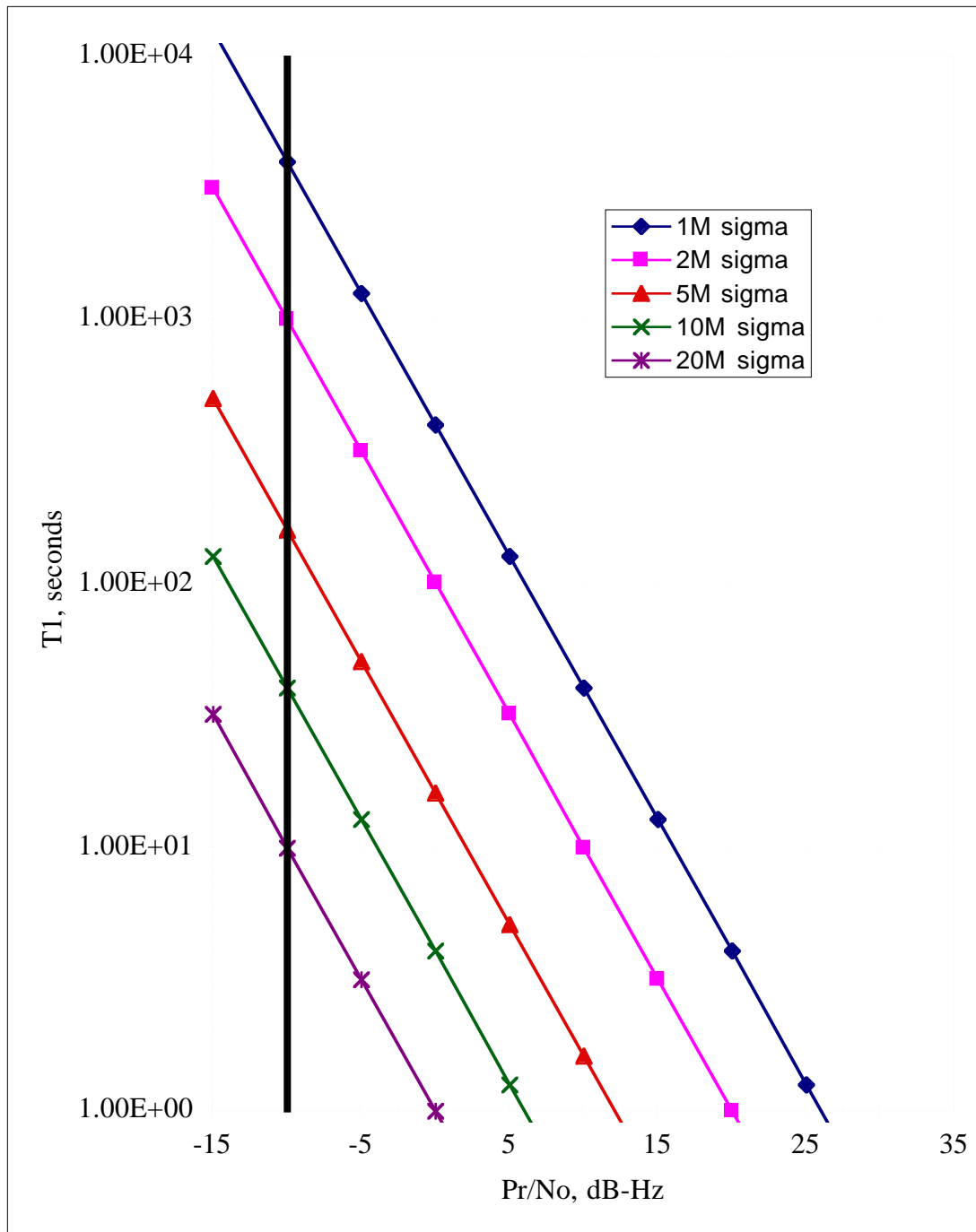
Figure 2.   Integration Time T1 vs. P_r/N_o, Clock Frequency Fc = 1 MHz, Sine-Wave or Square-Wave Ranging

Figure 3.   Integration Time T1 vs. P_r/N_O, Clock Frequency F_C = 500 kHz,
Sine-Wave Ranging

Figure 4.   Integration Time T1 vs. P_r/N_O, Clock Frequency F_C = 250 kHz,
Sine-Wave Ranging

Figure 5.   Integration Time T1 vs. P_r/N_O, Clock Frequency F_C = 125 kHz, Sine-Wave Ranging

Figure 6.   Integration Time T1 vs. P_r/N_O, Clock Frequency F_C = 62.5 kHz, Sine-Wave Ranging

Figure 7.   Integration Time T1 vs. P_r/N_O, Clock Frequency $F_C = 31.25$ kHz, Sine-Wave Ranging

Figure 8.   Integration Time T1 vs. P_r/N_O, Clock Frequency $F_C = 15.625$ kHz, Sine-Wave Ranging

Figure 9.   Integration Time T1 vs. P_r/N_O, Clock Frequency $F_C = 500$ kHz, Square-Wave Ranging
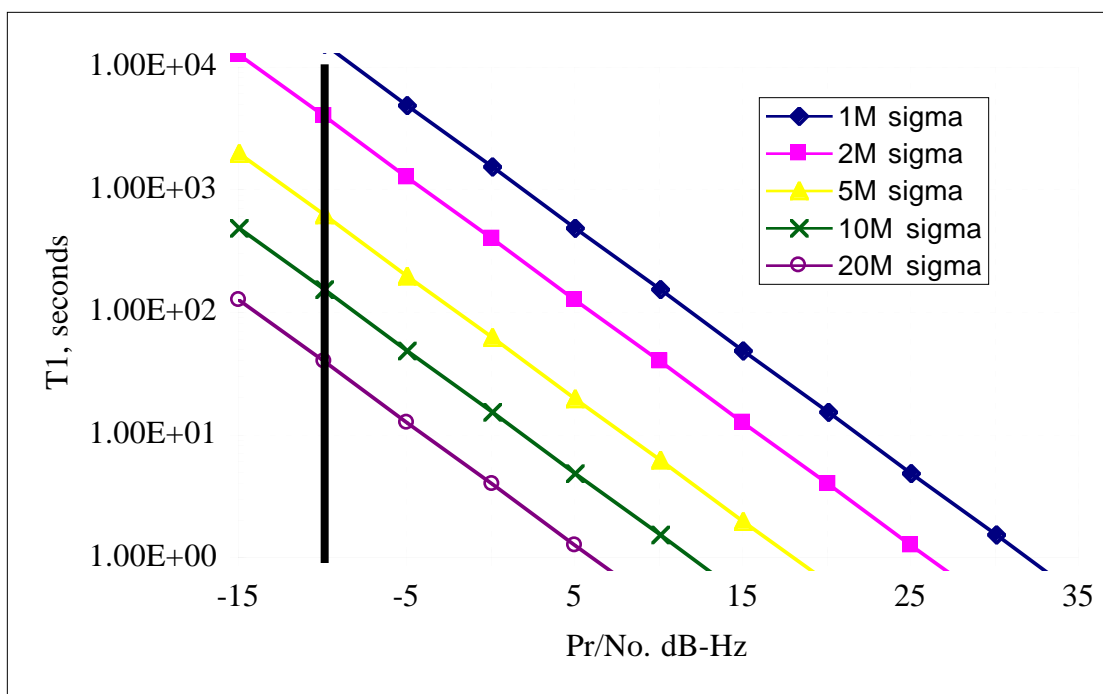

Figure 10.   Integration Time T1 vs. P_r/N_O, Clock Frequency $F_C = 250$ kHz, Square-Wave Ranging

Figure 11.   Integration Time T1 vs. P_r/N_O, Clock Frequency F_C = 125 kHz, Square-Wave Ranging
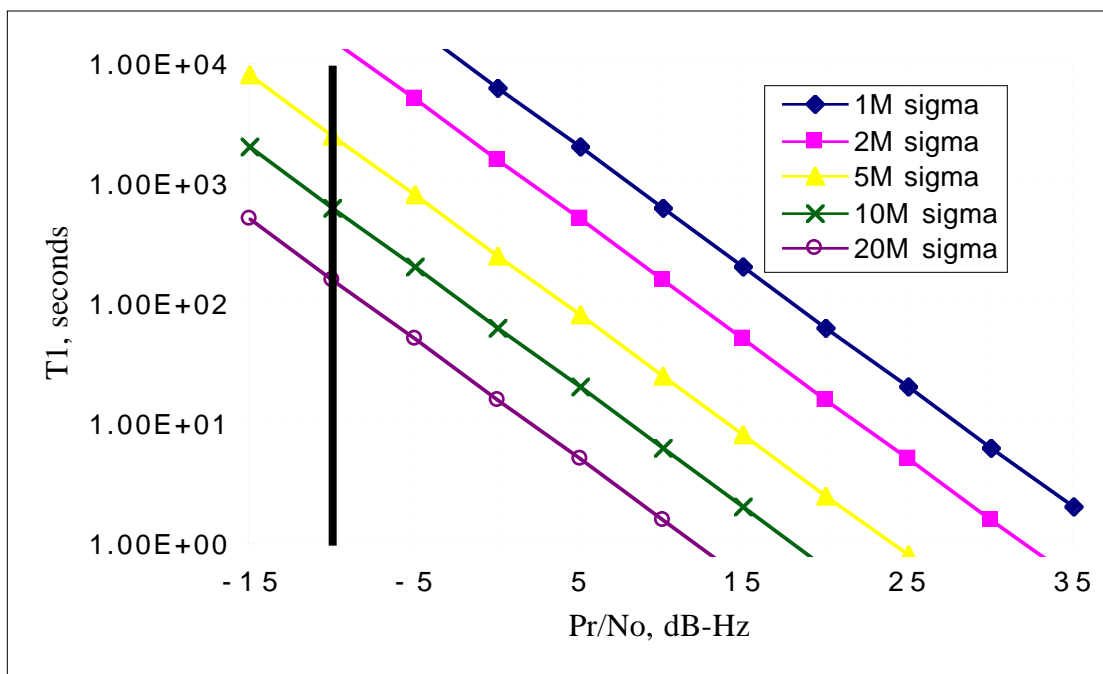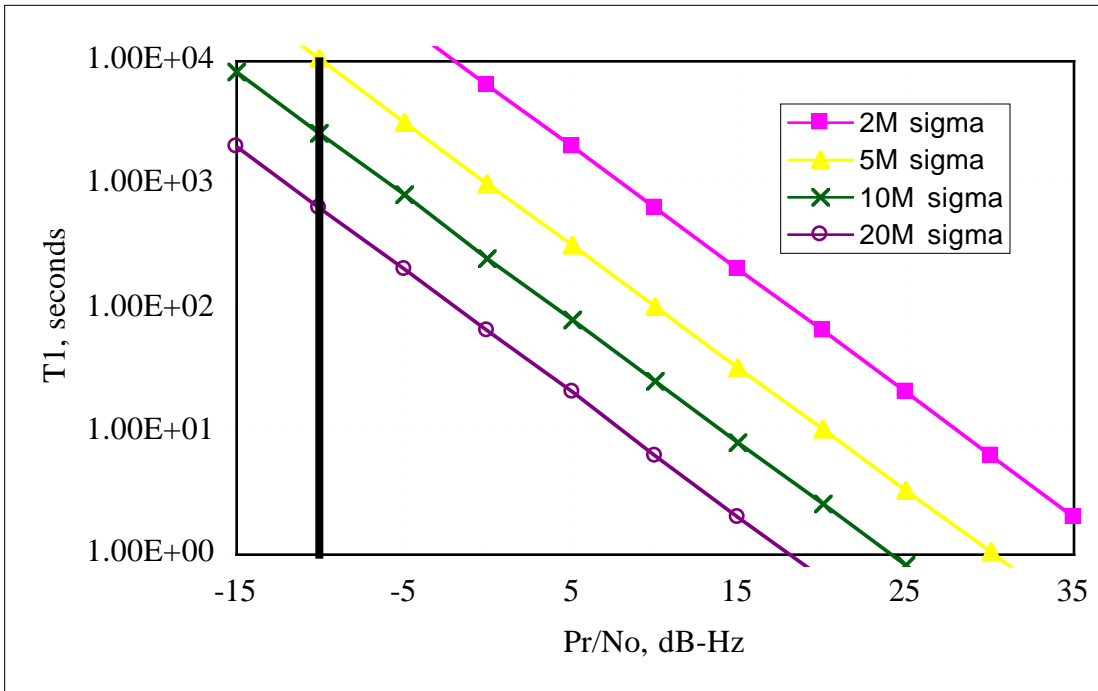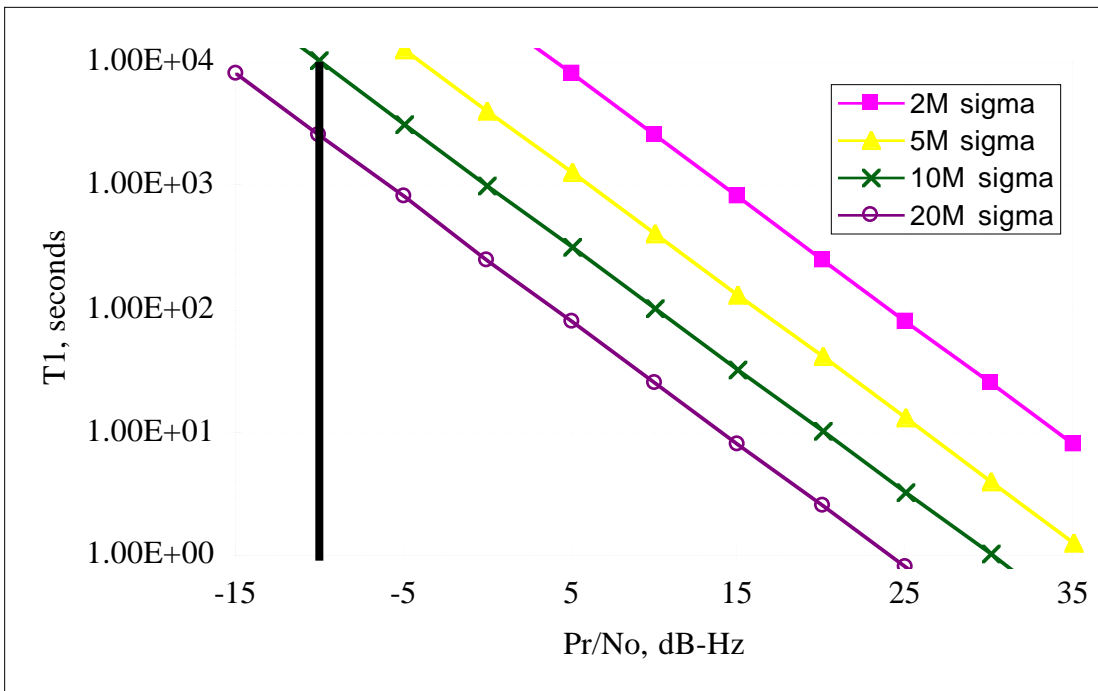
Figure 12.   Integration Time T1 vs. P_r/N_O, Clock Frequency F_C = 62.5 kHz, Square-Wave Ranging
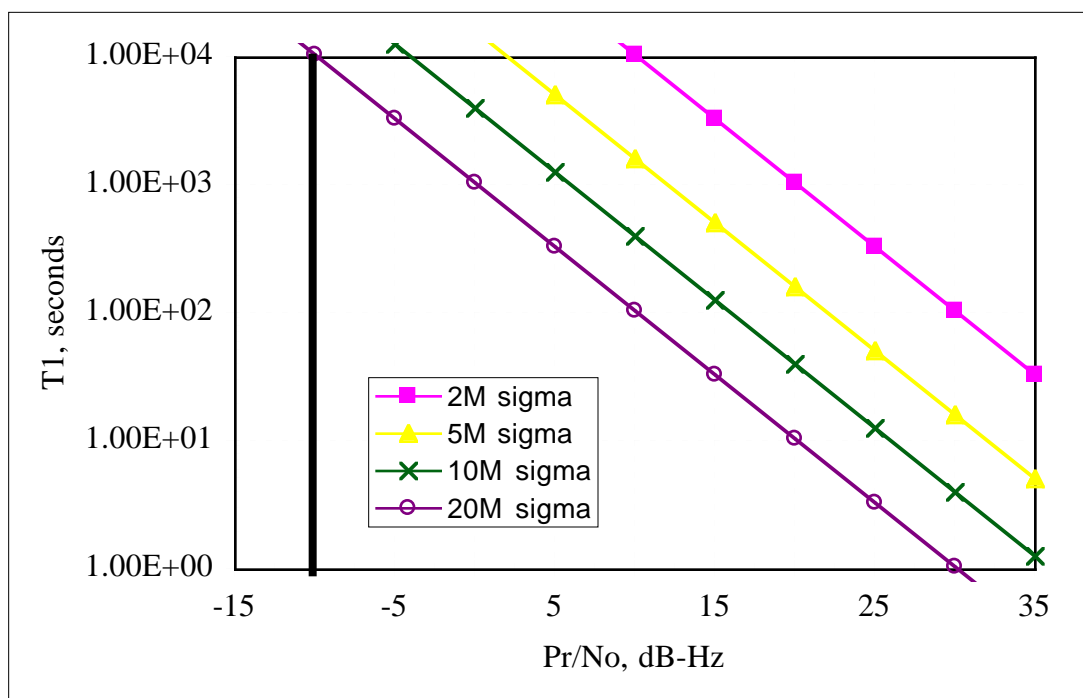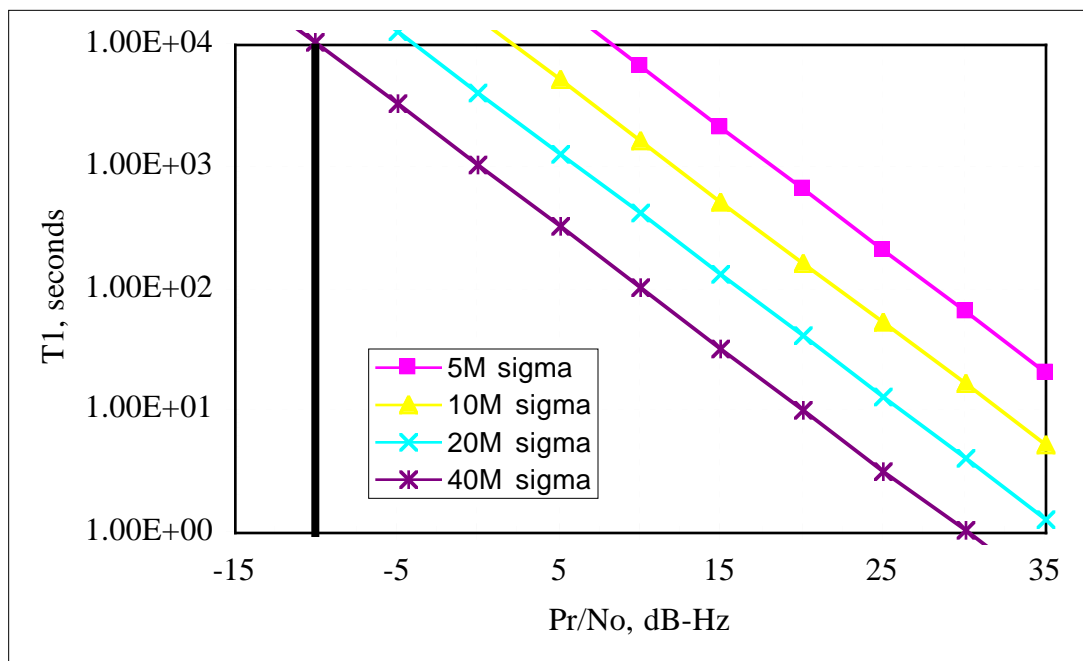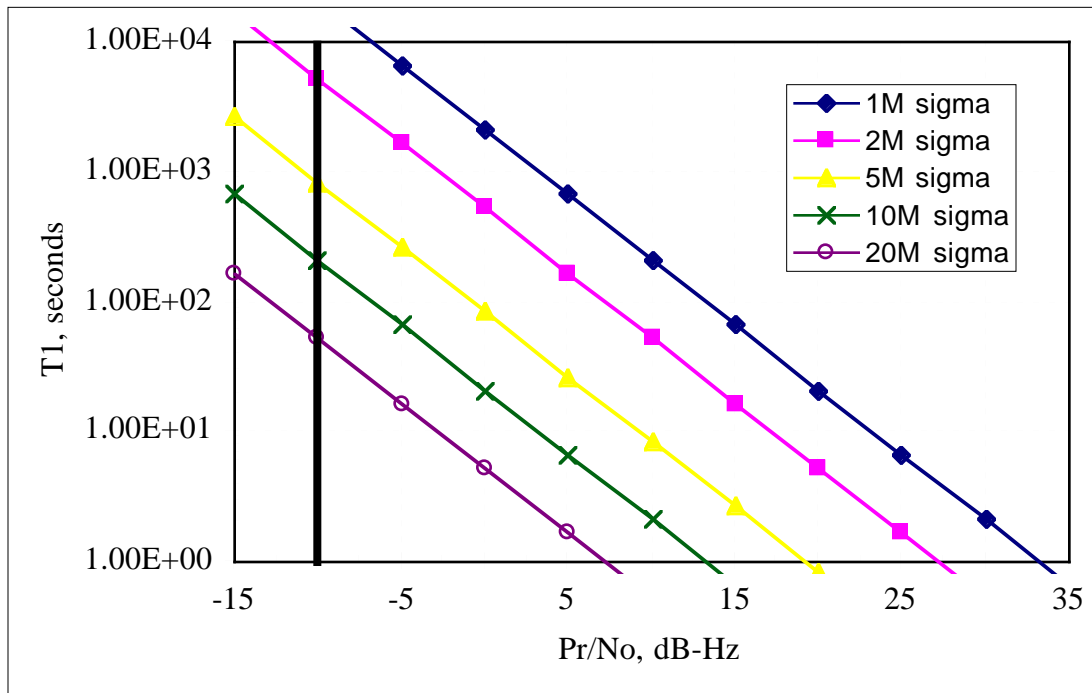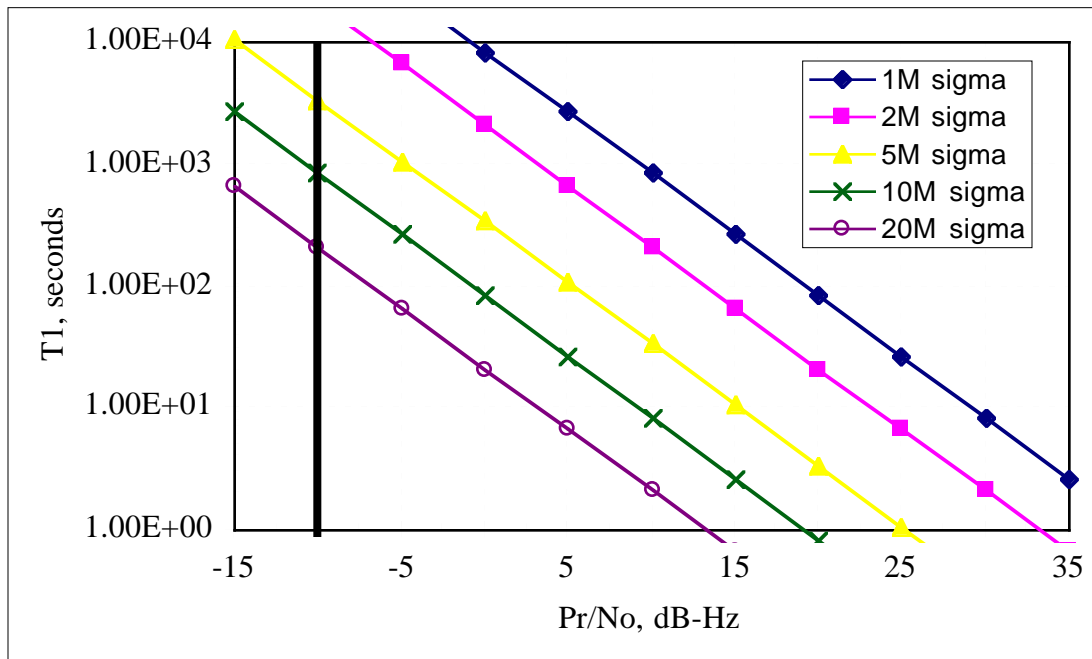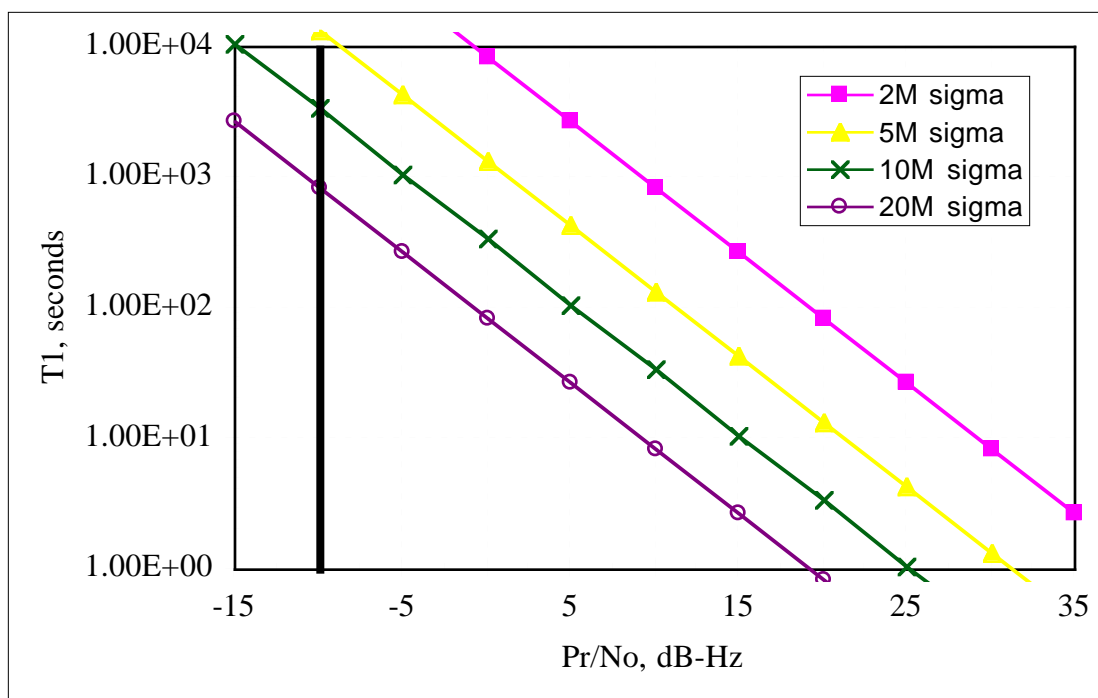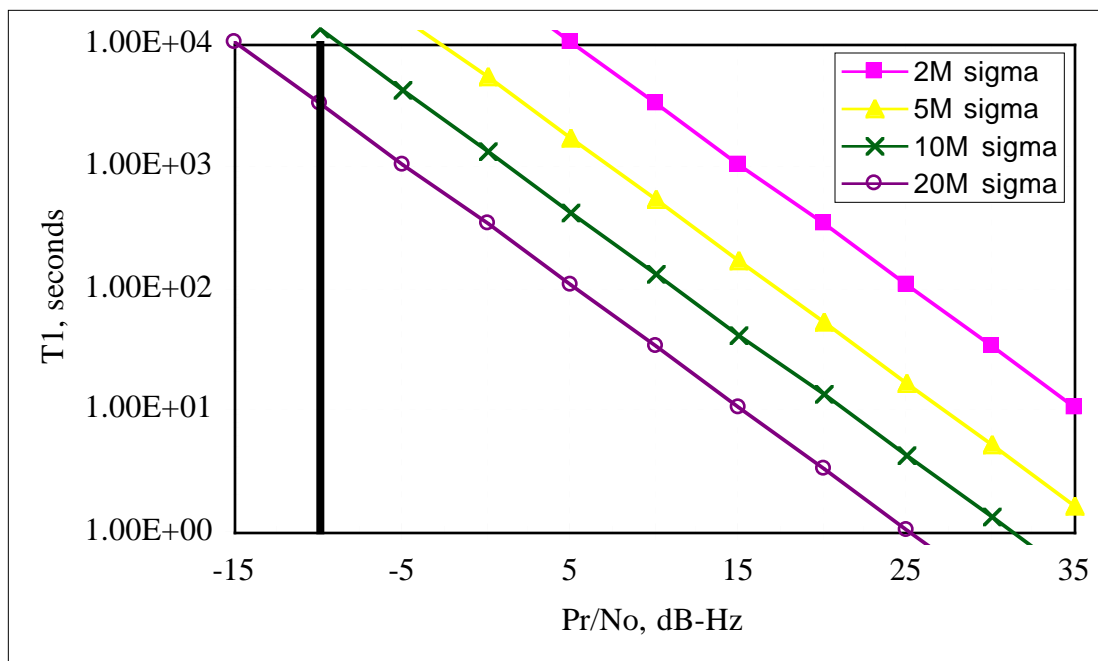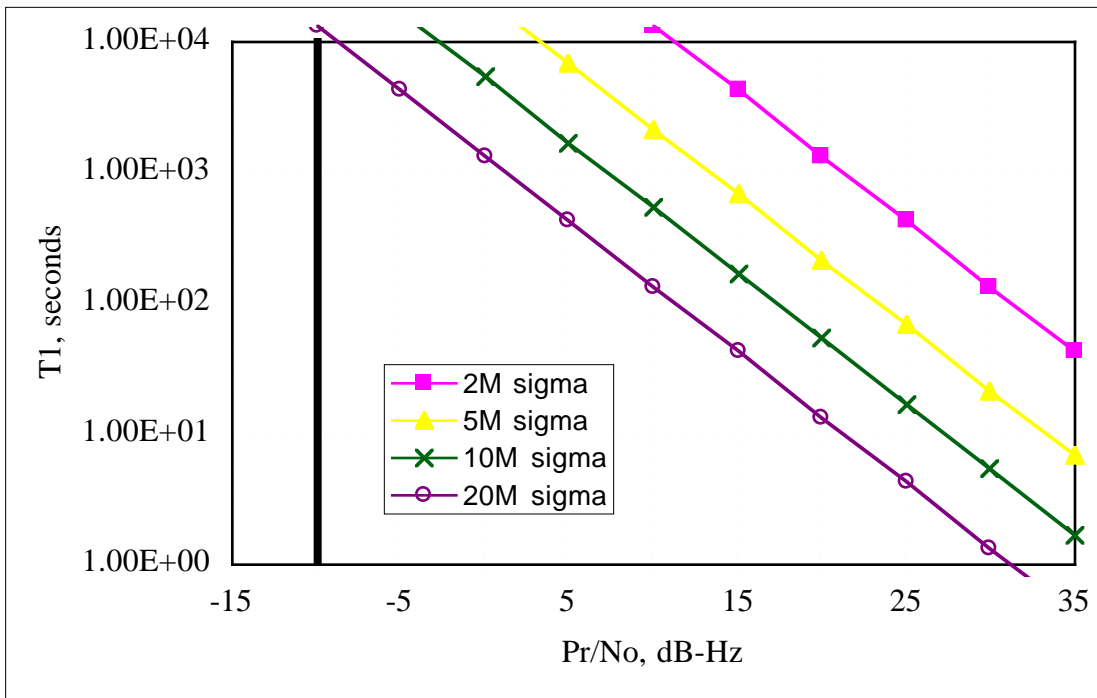
Figure 13.   Integration Time T1 vs. P_r/N_O, Clock Frequency F_C = 31.25 kHz, Square-Wave Ranging
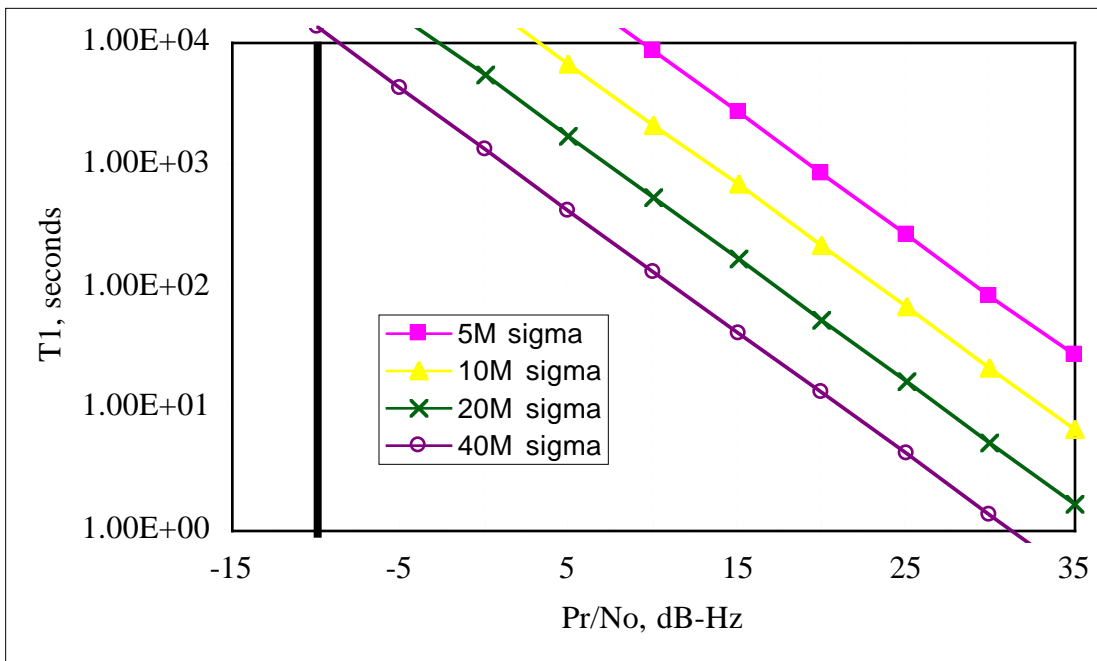

Figure 14.   Integration Time T1 vs. P_r/N_O, Clock Frequency F_C = 15.625 kHz, Square-Wave Ranging

2.2.4.2   ***T2***. T2 is the integration time for each of the lower frequency components. It is a function of P_r/N_O and the probability of error in acquiring all components (excluding the clock). In general, T2 is given by the following equation:

$$T2 = \frac{1}{P_r\!\big/N_0} \times \left\{ \text{InvErf}\left[2(1 - P_e)^{\frac{1}{n-1}} - 1 \right] \right\}^2 \text{, (seconds)}$$

where:

Pr/No	=	the ranging signal to noise spectral density.
InvErf[*]	=	the inverse error function of the * quantity.
P_e	=	the probability of making an error in all (n-1) components.
n	=	the total number of components including the clock being acquired.

Figure 15a through Figure 15c show T2 versus P_r/N_O for various P_e and n. An appropriate T2 for ranging operations can be determined from these curves by choosing the desired n, P_e, and the estimated P_r/N_O.

2.2.4.3   ***T3.*** T3 is the integration time for Differenced Range Versus Integrated Doppler (DRVID) measurements (see Paragraph 2.3.4 for further discussion on DRVID). Since the phase information is already available from the clock acquisition, T3 can be an integer number of seconds smaller than T1. Since the SRA spends 1/8 of the specified T1 to seek an optimal phase (45-degrees) for the correlation process, a good choice of T3 is given by:

         T3   =   T1x7/8 (rounded to the nearest integer).

2.2.4.4   ***Cycle Time.*** Cycle time is the total time that the SRA spends to perform measurements for the clock, the (n-1) components, and the DRVID's. Alternatively, it is the duration to complete one range acquisition. The cycle time (CYC) is automatically calculated by the SRA, and it is given by the following formula:

         CYC = (2+T1) + (1+T2)(n-1) + DRVN·(2+T3) + 1 , (seconds)

where:

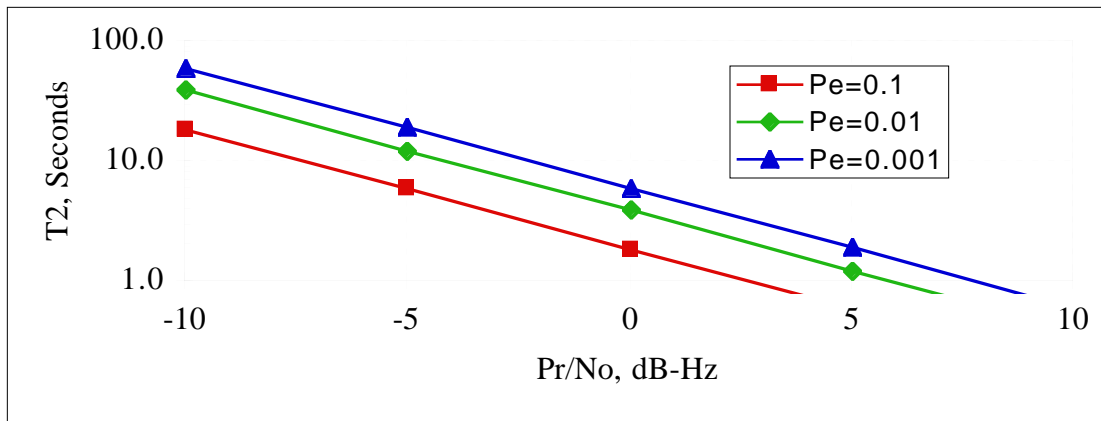|		
T1	=	clock integration time
T2	=	component integration times
T3	=	DRVID integration time
n	=	the total number of components including the clock
DRVN	=	the number of DRVID's specified for the acquisition

Figure 15a.   Code Component Integration Time T2 vs. P_r/N_O for Various Probability of Error and 5 Components
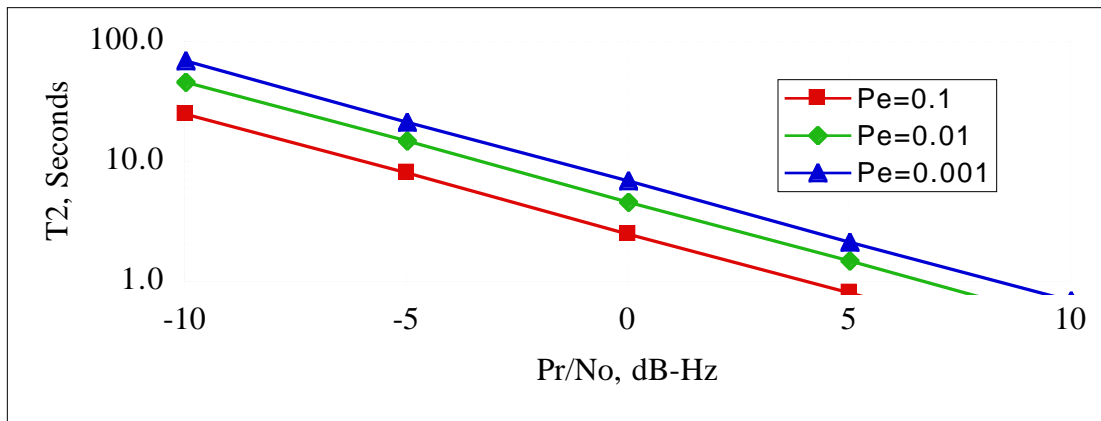
Figure 15b.   Code Component Integration Time T2 vs. P_r/N_O for Various Probability of Error and 10 Components
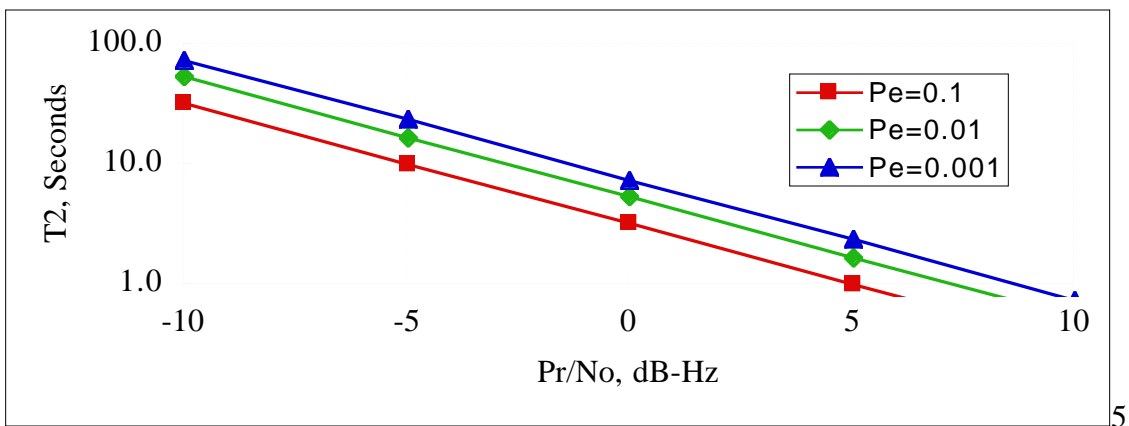
Figure 15c.   Code Component Integration Time T2 vs. P_r/N_O for Various Probability of Error and 20 Components

For a typical 8-hour tracking pass, it is recommended that the cycle time (CYC) is within the following limits:

Soft limit: CYC <= 30 minutes

Hard limit: CYC <= 55 minutes

The chance of getting a desired number of good range points decreases substantially as the cycle time approaches the 55-minute limit. Any glitch occurring in the system during the time of measurement will cause a range point to become invalid. It is better to stay closer to or within the soft limit.

2.2.5   *Modulation   Index*

In ranging operations, square-wave codes are modulated on the uplink carrier by the exciter phase modulator. This results in the carrier power being reduced and put into the sidebands. The sideband power here is the same as ranging power. The expressions for carrier power and ranging power are given in terms of the modulation index as follows:

$$P_c = P_t\left(\cos^2\theta\right), \text{ numeric, units of power}$$

$$P_r = P_t\left(\sin^2\theta\right), \text{ numeric, units of power}$$

where:

P_c =   the carrier power

P_r =   the ranging power

P_t =   the total signal power before modulation (that is, $P_t = P_c + P_r$)

θ =   the modulation index in radians

Therefore, the carrier suppression in dB is given by:

$$\frac{P_c}{P_t} = 10\log\left(\cos^2\theta\right), \text{ dB}$$

The modulators used in the DSN operate over the range of 0.1 to 1.6 Radians, peak.

Example: An unmodulated signal is received by a spacecraft with P_t = -100 dBm. When this signal is modulated by square waves of a 30-degrees modulation index, the carrier power (P_c) becomes -101.25 dBm (suppressed by -1.25 dB), and the ranging (sidebands) power (P_r) is -106.0 dBm   (P_r = -100 dBm + 10 Log (0.25)).

2.2.6   *Frequency Chopping*

The modulation spectrum moves closer to the carrier as a ranging acquisition steps through the code components to lower frequencies. If the spectrum becomes too close, one of two things will happen: 1) the receiver tracking loop will follow the waveform and track out the code(s); or 2) interference will occur to the telemetry or command modulation. A frequency chopping modulation function can be enabled to prevent the above unwanted problems. The function is defined by:

$$C = C_m \oplus C_c$$

where:

C is the modulation

C_m =   the square-wave modulation of the component, m, being chopped

C_c =   the square-wave modulation of the clock component

$\oplus$ denotes modulo 2 addition

The chopping process results in a power spectrum for a sideband pair relative to the ranging power as follows:

$$\frac{P_k}{P_r} = 10\log\left\{8 \times \left[\frac{\tan\left(\frac{k\pi}{2^{m-c+1}}\right)}{k\pi}\right]^2\right\}, \quad (\text{dB})$$

where:

P_k =   the power of the k-th odd sideband pair (there are no even harmonics)

P_r =   the total ranging power (all sidebands)

m   =   the component number being chopped

c   =   the number of the clock (3 to 10)

k   =   the odd sideband-pair number of the component being chopped

The physical meaning of chopping can best be illustrated by Figure 16(1). This Figure shows components C5, C6, and C7 being chopped by the 1-MHz clock, C4. The dotted lines indicate where the edges of the components would be without chopping. Note that C4 $\oplus$ C5 is the same as C5 shifted 1/4 cycle to the left. This happens when a component is chopped by another component of twice the frequency.

The component at which chopping starts is selectable. The SRA unconditionally turns chopping on when it reaches component number 10 ($\approx$16 KHz) so that the signal is never closer than 16 KHz to the carrier.
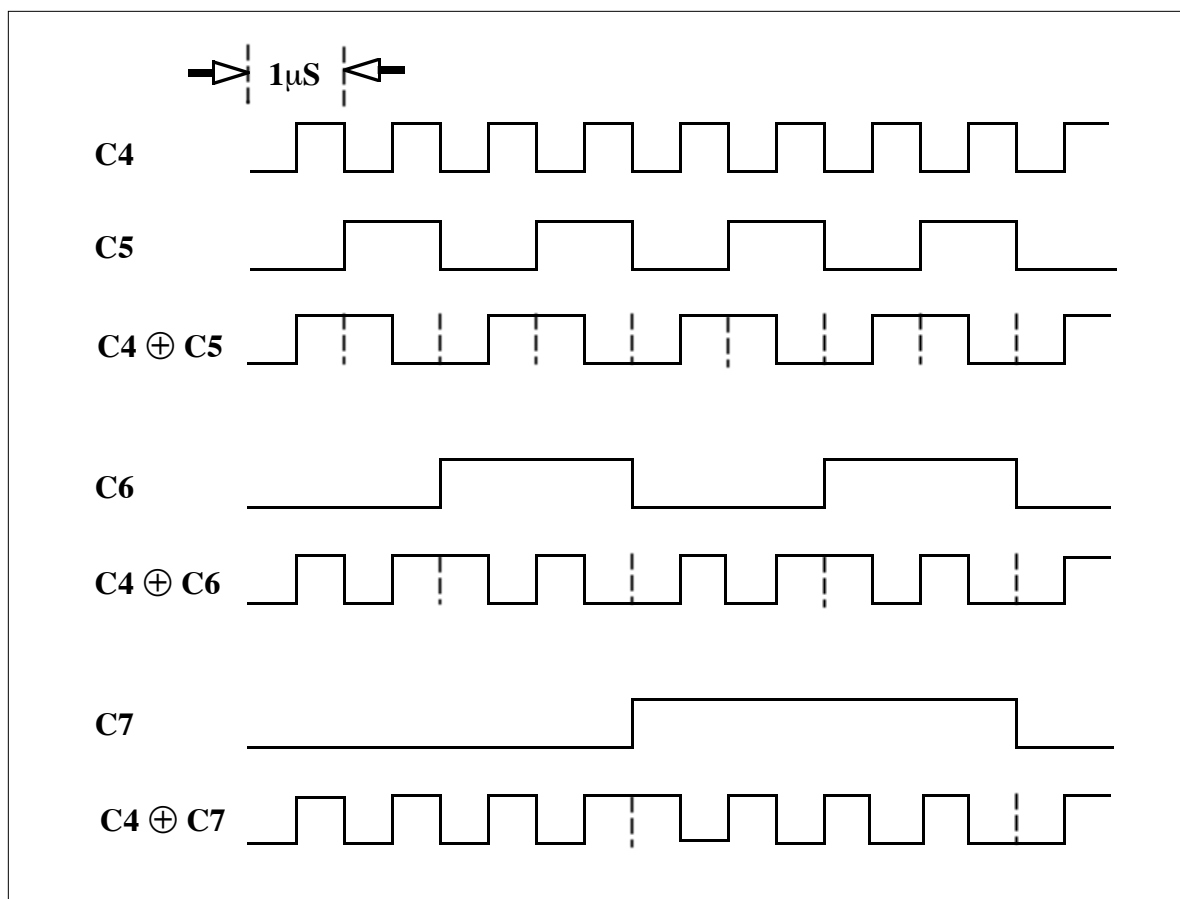
Figure 16. Chopping of C5, C6, and C7 (by C4)

2.2.7 Other Parameters

There are four other parameters which must also be specified for ranging operations. Their meaning and usage are briefly summarized below.

2.2.7.1 Tolerance. Tolerance is used to set the acceptable limit of a given Figure of Merit (FOM). Tolerance may be selected over the range of 0.0% to 100.0%. On one hand, if tolerance is set to 0.0%, all range acquisitions will be declared valid. On the other, if it is set to 100.0%, all range acquisitions will be declared invalid.

A typical value set for tolerance is 99.9%. This value will flag acquisitions which have a 99.9% or better chance of being good as valid, and the rest as invalid.

The FOM (See Paragraph 2.3.3 for additional discussion) is an estimate of the goodness of an acquisition, based on the P_r/N_o measurement made from integrating the clock. An acquisition is declared valid or invalid depending upon the following criteria:

FOM ≥ Tol   =>   Valid

FOM < Tol   =>   Invalid

2.2.7.2   ***Servo.*** When Servo is enabled, the local Doppler-corrected components will be shifted back into phase with the received components. Servo is used to correct distortions of the data due to charged particle effect using DRVID information (See Paragraph 2.3.4 for a discussion of DRVID). The correction is made by setting a proper Servo value.

Servo has a value between 0 and 1.0. It should be set to 1.0 with a noiseless signal, but if the noise level is too high, no DRVID refinement is possible then Servo should be set to 0. Note that if Servo is 1.0, the correction is made immediately; however, if Servo is set to a fractional value between 0 and 1.0, that fraction of the correction will be done on any one DRVID measurement.

2.2.7.3   ***Inversion***. The inversion parameter is used to invert the received ranging signal depending on the receiving system of a DSS. All receivers in the DSN, with the exception of the receivers in the 34-m STD subnet, invert the ranging signal. Note that spacecraft may also invert the ranging signal, however, none currently in operation do.

2.2.7.4   ***Pipe***. The "Pipe" parameter (for pipelining) specifies the number of range acquisitions to be made. This parameter enables multiple measurements to be initiated before the first measurement is completed. Only one acquisition is made if Pipe is disabled. If it is enabled, range measurements will be made until the total number of acquisitions reaches 32767 or until the specified number of acquisitions. In other words, the number of range acquisitions that can be performed is between 1 and 32767.

2.3   *Measurement Process*

The SRA transmitter coder uses a reference frequency (denoted by F66 in this Document) to generate a sequence of square waves (or binary codes). This code sequence is phase-modulated onto the uplink carrier. The measurement process begins when this signal is received by the SRA one RTLT later.

Prior to the receive time, T_O, the SRA receiver coder, referenced to the same F66, produces a replica of the uplink sequence. The two coders are synchronized so that they operate at the same frequency and phase.

At T_O, the synchronization is ended and a Doppler reference is used to advance or retard the phase of the replica (the Doppler modification essentially freezes the range at T_O when the synchronization ended). This Doppler-modified replica is sampled into an in-phase component (I_c) and a quadrature component (Q_c). These two components are correlated with the demodulated receiving code to produce the correlation values V_I and V_Q. The V_I's and V_Q's are used to compute the angle and amplitude of the received code; hence, the phase and signal strength are determined. The following paragraphs provide further detail.

The measurement of the phase (angle) displacement of the clock provides the resolving capability of the range measurement (See Table 1). Once the phase displacement is

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determined, the receiver coder is shifted by this displacement amount to produce a zero-phase shift in the in-phase channel. Since the remaining components are phase-coherent with the clock component, it is only necessary to determine if each component is in or out of phase with the previous component. This is done by integrating the V_I's and V_Q's for the time T2 specified during initialization. If each component is in phase, no action is necessary; if one is out of phase, that component and the remaining components are shifted by half its period. This process is repeated for each component. The sum of the required shifts (plus the clock-phase shift) is the phase delay between the transmitted and received signals, and the range is determined. Figure 17 illustrates the process graphically.

2.3.1 *Range*

The SRA measures 2-way range, the Round Trip Light Time (RTLT), by determining the phase difference between the transmitted and received modulation. This phase displacement (τ) is computed by the following expressions:

Sine-wave ranging:

$$\tau = \text{atan2}\left(\sum V_Q, \sum V_I\right), \text{ (radians)}$$

Square-wave ranging:

$$\tau = \text{SGN}\left(\sum V_Q\right) \times \frac{1}{4} \times \left(1 - \frac{\sum V_I}{\left|\sum V_Q\right| + \sum V_I}\right), \text{ (cycles)}.$$

where:

V_I and V_Q	=	the in-phase and quadrature correlation values.
atan2(y,x)	=	the arctangent function that produces an angle in the proper quadrant.
SGN(*)	=	$\begin{vmatrix} +1, & * \geq 0 \\ -1, & * < 0 \end{vmatrix}$

For ranging operations, the above τ of different dimensions are converted to a measurement unit called Range Units (RU, an RTLT unit). RU's have the dimension of seconds. By definition, one RU equals to one sixteenth of the period of a reference frequency, i.e.

$$RU = \frac{1}{16} \times \frac{1}{F66}, \text{ (seconds)}$$

where F66 is the reference frequency, F66s or F66x, discussed earlier.
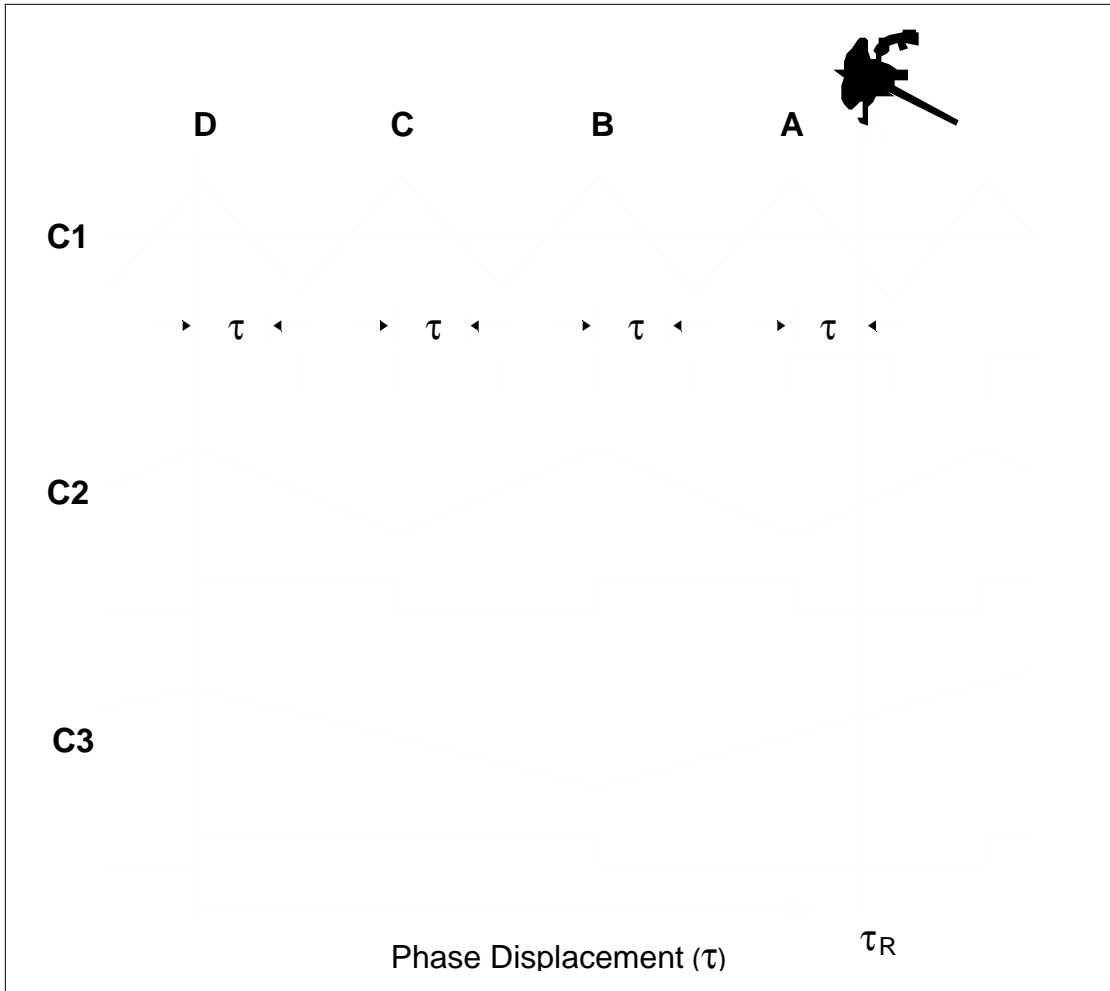
Figure 17. Component Acquisition Process

Notes:

1. Assume that the range to the spacecraft results in $\tau = \tau_R$ and that the range uncertainty is in the interval defined by C2 and C3.

2. Measurement of the phase offset of C1 indicates that the correlation amplitude is not at a peak value. The receiver coder is shifted (delayed) to bring the correlation value to a positive peak, A.

3. At A, the correlation function for C2 is at a negative peak; thus C2 is out of phase. The reference code is shifted by half the period of C2 (to bring it into phase), arriving at B.

4. At B, C3 is out of phase with C2. The reference code is shifted by half the period of C3, arriving at D.

5. The sum of the phase shifts required to bring all components into phase is τ_R, the range measurement.

Using the above RU equation, one may convert the measurement obtained in RU's to physical quantities such as time (nanoseconds) and distance (meters). For example, if the F66 used in a range measurement is 66 MHz and suppose the measurement obtained is 6,500,000 RU, then the equivalent RTLT delay is 6.155 milliseconds and the one-way distance is about 923295 meters.

2.3.2 *Pr/No*

The actual ranging power-to-noise spectral density (Pr/No) is evaluated at the end of the integration of all in-phase and quadrature correlation values for the clock (see Paragraph 2.2.2 for an additional discussion on clocks and components). It combines ranging system performance with receiver noise. This ratio is given by:

$$\frac{P_r}{N_0} = 10\log\left(\frac{\text{Ranging Signal Power }(P_s)}{\text{Noise Power}(P_n)} \times \text{Bandwidth(BW)}\right), \text{(dB)}$$

where, depending on a ranging operation, Ps is evaluated by two different expressions.

Sine-wave operation:

$$P_s = \frac{\left(\sum V_I\right)^2 + \left(\sum V_Q\right)^2}{N^2};$$

Square-wave operation:

$$P_s = \frac{\left(\left|\sum V_I\right| + \left|\sum V_Q\right|\right)^2}{N^2}$$

where:

V_I and V_Q are the correlation values.

N is the total number of samples collected during the clock acquisition.

Noise power is estimated by adding the variances of the in-phase and quadrature correlation samples:

$Pn = Var_I + Var_Q$,

where:

Var_x is the variance function:

$$Var_x = \frac{\sum\left(x^2\right)}{N} - \frac{\left(\sum x\right)^2}{N^2},$$

in which x is replaced by the correlation sample V_I's and V_Q's, and N is the number of samples.

Finally, BW is the process bandwidth of the SRA. The ratio P_r/N_o is evaluated using pairs of 0.1-second long correlation samples. Therefore, the BW used in calculating P_r/N_o is the reciprocal of 2 x 0.1 sec or 5 Hertz.

2.3.3   Figure of Merit

The Figure of Merit (FOM) is a probability measure which estimates the chance of successful acquisition of all lower frequency codes. The probability of making at least one error in acquiring n-1 codes is:

$$P_e = 1 - \frac{1}{2^{n-1}} \times \left[\text{Erf}\left(-\sqrt{\frac{P_r}{N_0} \times T2} \right) + 1 \right]^{n-1}$$

where:

n is the number of components including the clock.

Erf(*) is the error function.

P_r/N_0 is the ranging power-to-noise ratio.

T2 is the integration time for each of the lower frequency components.

Alternatively, the probability of getting all good measurements is:

$$P_c = 1 - P_e$$

This FOM (FOM = 100 * P_c in %) predicts a statistical outcome. It is only a reference by which the users may judge the validity of a range measurement. FOM is also discussed in Paragraph 2.2.7.1 (Tolerance).

2.3.4   Differenced Range Versus Integrated Doppler

Differenced Range Versus Integrated Doppler (DRVID) may be used to study the electron content in the transmission medium since group delay is increased by increasing electron content while phase delay is decreased. The spinning of a spacecraft, which causes a shift in Doppler, can also be observed by measuring DRVID's.

DRVID is defined by the difference between two group delay measurements and the phase change integrated over the same time frame. In other words, integrating the phase change between two timetags t_j and t_k, and subtracting the result from the difference between two measurements of the group delay (with the same timetags) will give DRVID. It can be expressed by:

$$\text{DRVID}(t) = \rho_g(t_j) - \rho_g(t_k) - \int_{t_k}^{t_j} F_c(t)dt,$$

where:

$\rho_g(t_j)$ and $\rho_g(t_k)$ are the group delay measurements at t_j and t_k respectively.

$F_C(t)$ is the received code frequency at time t.

2.4 *Ratio of Downlink Ranging Power to Total Power*

For the type of currently used simple turn-around ranging channel, the ratio of power in the fundamental ranging sidebands to the total signal power in the downlink is a function of the uplink ranging signal-to-noise ratio. It is given by (2):

$$\left[\frac{P_r}{P_t}\right]_{DN} = 2J_1^2\left[\sqrt{2}\cdot\beta_{DN}\sqrt{\frac{\Gamma_{RNG/UP}}{1+\Gamma_{RNG/UP}}}\right]\cdot\exp\left[-\frac{\beta_{DN}^2}{1+\Gamma_{RNG/UP}}\right]$$

where:

$\left[\dfrac{P_r}{P_t}\right]_{DN}$ is the ratio of power in fundamental ranging sidebands to total signal power for downlink,

$J_1[*]$ is the Bessel function of the first kind of order one,

β_{DN} is the downlink ranging modulation index, radians rms,

$\Gamma_{RNG/UP}$ is the uplink ranging signal-to-noise ratio at the output of the transponder's ranging channel filter, given by:

$$\Gamma_{RNG/UP} = \frac{8}{\pi^2}\left[\frac{P_r}{N_0}\right]_{UP}\cdot\frac{1}{B_{RNG}},$$

in which:

$\left[\dfrac{P_r}{N_0}\right]_{UP}$ is the ranging power to noise spectral density ratio at input to the transponder's ranging channel filter, Hertz

B_{RNG} is the transponder's ranging channel filter bandwidth, Hertz. The typical value for B_{RNG} is 1.5 MHz.

Figure 18 is a plot of $\left[\dfrac{P_r}{P_t}\right]_{DN}$ versus $\Gamma_{RNG/UP}$ for selected values of β_{DN}. For deep space missions, the uplink ranging signal-to-noise ratio is usually quite small, and the operating point lies on the steep curve on the left side of Figure 18. In this regime,

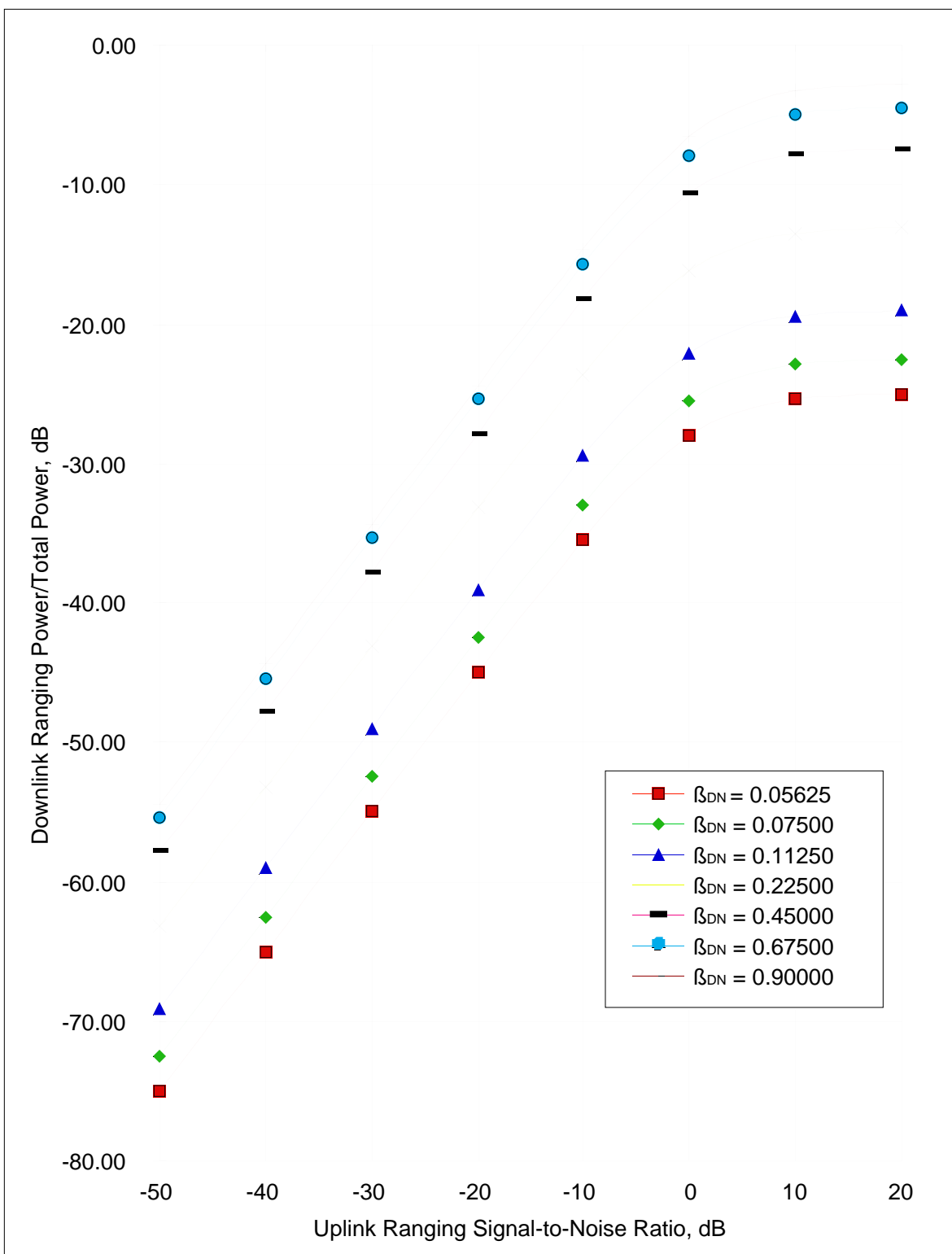$$\left[\frac{P_r}{P_t}\right]_{DN} = \Gamma_{RNG/UP}\ \beta_{DN}^2\exp(-\beta_{DN}^2),\quad \Gamma_{RNG/UP}\ \ll 1.$$

Figure 18. $\dfrac{P_r}{P_t}$ as a Function of $\Gamma_{RNG/DN}$ for Selected Values of β_{DN}

This equation is a good approximation for two-way ranging with most deep space vehicles.

The presence of uplink noise feeding through onto the downlink has two effects. The important effect is that valuable downlink power is robbed from the fundamental ranging sidebands. This effect is characterized by the above expressions for $\left[\dfrac{P_r}{P_t}\right]_{DN}$. The other effect is that the uplink noise has the potential to interfere with the fundamental ranging sidebands; in other words, the uplink noise might increase the noise floor of the two-way range measurement. It turns out that for most deep space missions, this second effect is very small and can be ignored.

2.5 *Range Corrections*

The SRA measurements include delays of equipment within the DSS as well as the spacecraft. These delays must be removed in order to determine the actual range referenced to some reference location at the antenna. Figure 19 illustrates the end-to-end range measurement in the DSN.

The DSN is responsible for providing three measurements to the project. They are the DSS delay, the Z-correction, and the antenna correction.

2.5.1 *DSS Delay*

The DSS delay is station and configuration dependent. It should be measured for every ranging pass. This measurement is called precal for pre-track calibration and postcal for post-track calibration. The former is done at the beginning of a ranging pass; the latter is only needed when there is a change in equipment configuration during the track, or precal was not performed due to a lack of time.

The delay is measured by a system setup which approximates the actual ranging configuration. The signal is transmitted to the sky, however, before reaching the feedhorn, a sample is diverted to a test translator through a range calibration coupler. The test translator shifts the signal to the downlink frequency, which is fed into the coupler. The signal flows through the Low Noise Amplifier (LNA) and receiver to the SRA for calibrating.

Figure 20 shows the signal path for a typical calibration of DSS delay. The solid lines identify the calibration path, the dotted lines are shown for completeness only.

2.5.2 *Z-Correction*

The delay in the microwave components ahead of the coupler and the airpath (the distance from the horn aperture plane to the subreflector, to the antenna aperture plane, and finally to the antenna reference location) must be added to the measurement. Also, the translator delay must be removed. A measurement called "Z-correction" is made to obtain an adjusted DSS delay.
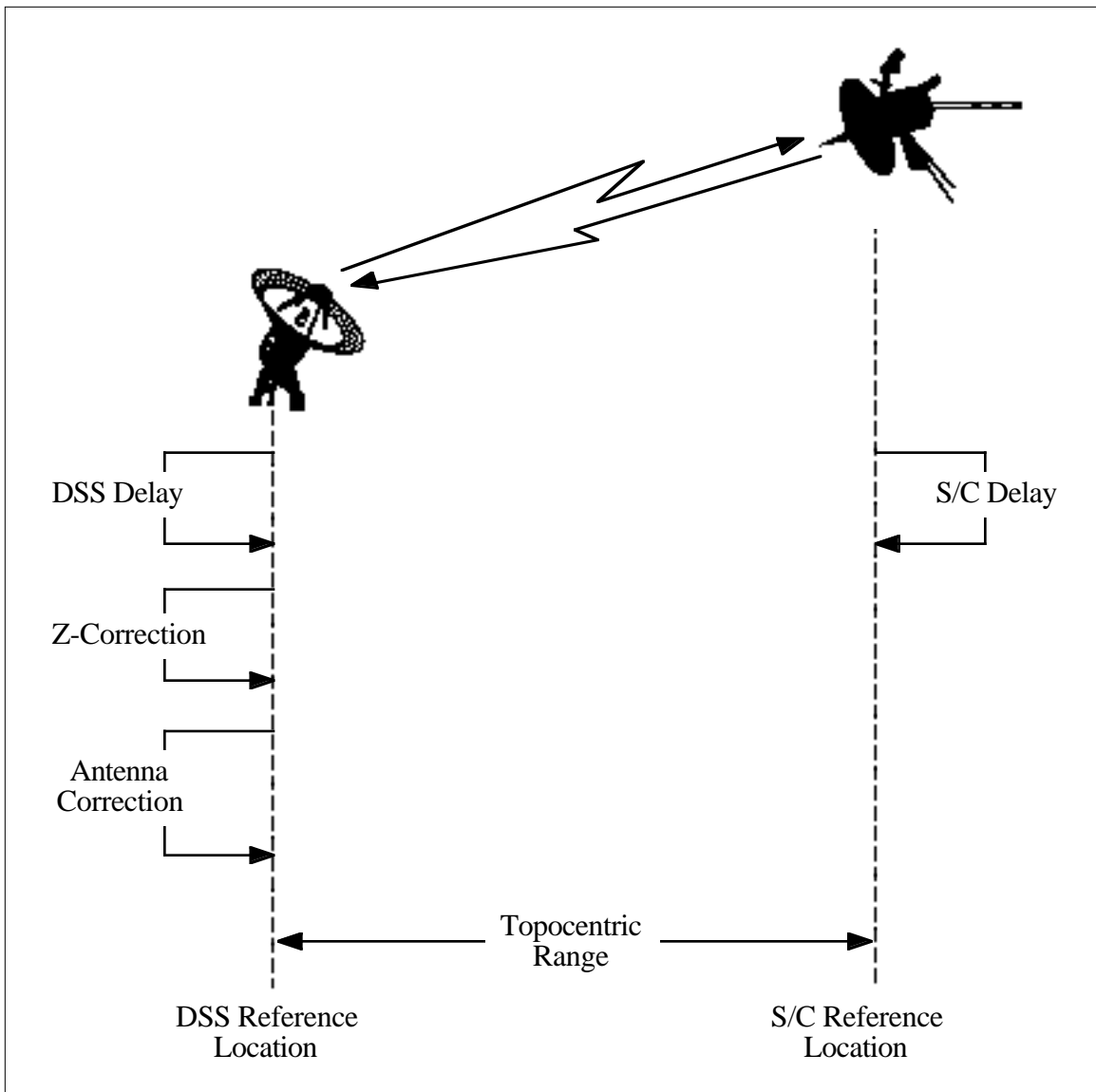
Figure 19. DSN Range Measurement

The Z-correction is given by the difference of two quantities: the translator delay and the microwave plus airpath delay. Figure 21 presents the equation used to calculate the correction and relates the terms in the equation to the physical structure of the antenna.

The test translator delay (T_{XLTR}) is measured by installing a Zero Delay Device (ZDD) in place of the test translator. The ZDD delay is known and measured in the laboratory, and from this the test translator delay can be calculated. This measurement is made approximately twice a year or when there are hardware changes in the signal path.
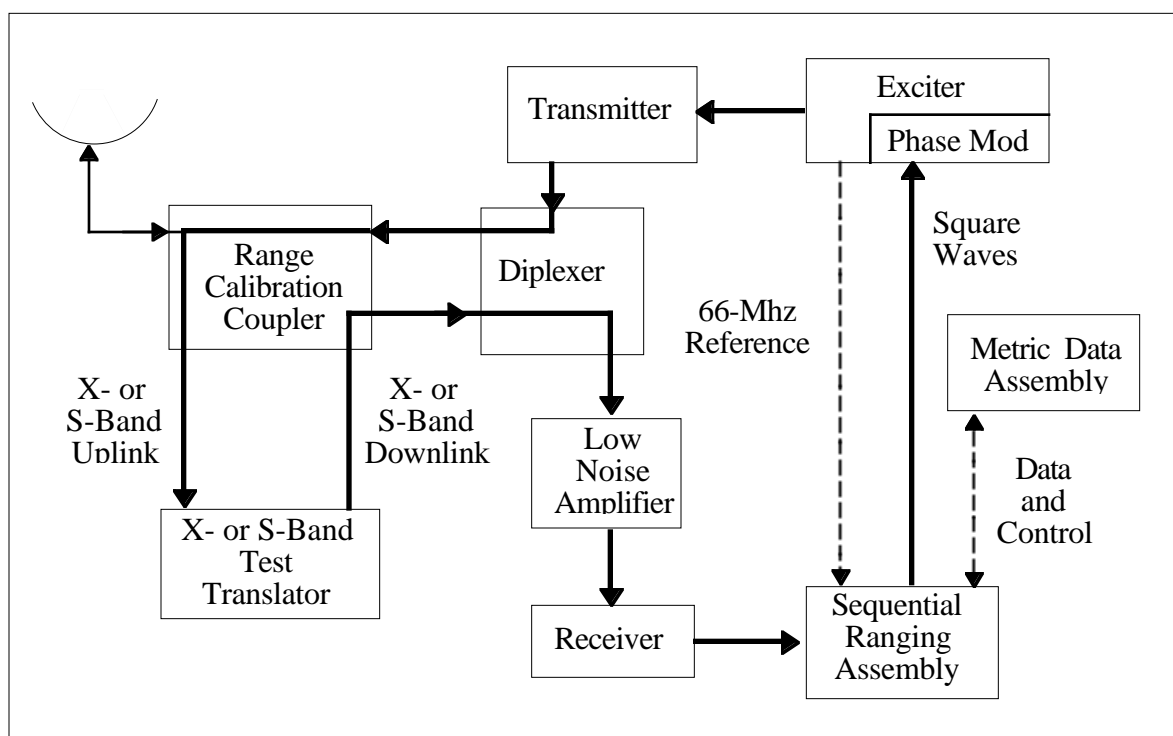
Figure 20. A Typical Signal Path of DSS Range Calibration

The microwave and airpath delays are measured by physically calibrating the microwave hardware components prior to installing them on the antenna. The antenna aperture plane, the horn aperture plane, and an antenna reference location are used to determine the actual airpath delay as shown in Figure 21. The antenna reference location (represented by the "X" in the figure) is the perpendicular intersection of the primary antenna axis with the plane of the secondary axis.

2.5.3   Antenna   Correction

There are three types of structurally different antennas in the DSN. They are the Azimuth-Elevation (Az-El) mount, the Hour Angle-Declination (HA-Dec, equatorial) mount, and the X-Y mount. The first type has an azimuth axis which perpendicularly intersects the elevation axis. The last two types have a primary and a secondary axes which are offset from each other. This offset causes the secondary axes (DEC axis and Y axis) to move relative to the Earth as the antenna rotates and adjusts its elevation about the primary axes (HA axis and X axis). The change of distance is calculated by the following antenna correction expression:

$$\Delta\rho_A = -b\cos\theta$$

Subreflector

TcUP

Antenna
Aperture
Plane

TcDN

TdDN

TdUP

Antenna

X

Reference
Location

Feed
Horn

Horn
Aperture
Plane

Tau4

Tau3

Range
Calibration
Coupler

Test
Translator

T_{XLTR}

Z-Correction = T_{XLTR} – [Tau3 + Tau4 + (TcUP - TdUP) + (TcDN – TdDN)]

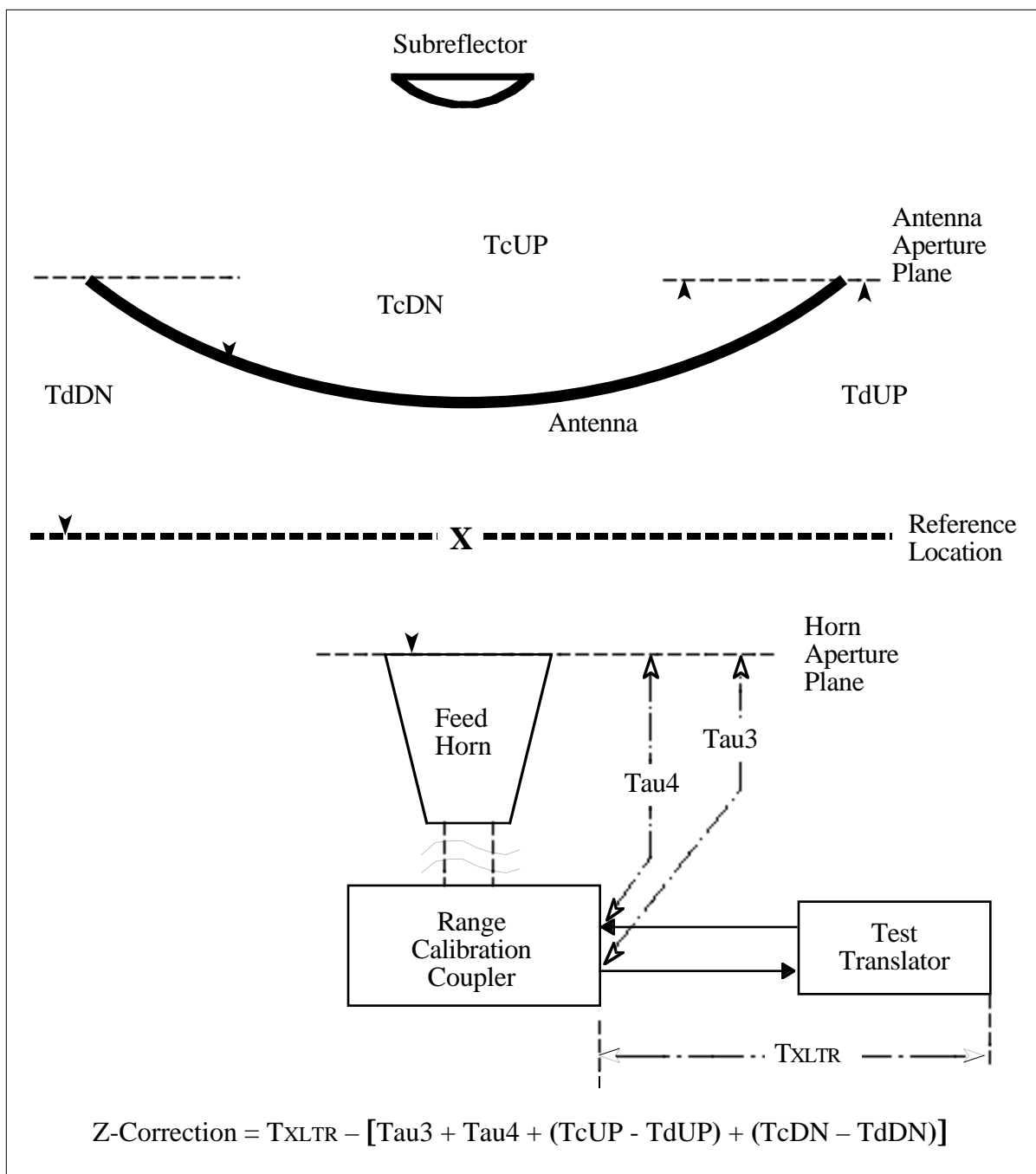Figure 21. Measuring The Z-Correction

where:

        b =   the displacement between the two axes:

                       6.706 m for the 34-m STD and 26-m subnets

                       0.000 m for the 34-m HEF, 34-m BWG and the 70-m subnets

        θ =   the angle of the elevation axis for Az-El antennas,

                       the angle of the declination axis for Ha-Dec antennas,

                       the angle of the Y axis for X-Y antennas.

2.6   *Error Contributions*

The ground system, the media, and the spacecraft contribute errors to range measurements. The error contributions of the media and spacecraft are outside the scope of this Document and will not be discussed here.

The round-trip one sigma range error of the DSN ranging system over a ranging pass has been estimated for the X-band system as 6.6 nanoseconds (about 1.0 meter one-way). The S-band system error has been derived as 14.7 nanoseconds (about 2.2 meters one-way).

Table 2 provides a breakdown of long-term error contributions due to calibration and errors inherent within the equipment of the various subsystems that constitute the total ground system.

Table 2. Round-trip One Sigma Range Error

Subsystem	X-band		S-band	
	Round-trip Delay (Nanoseconds)	One-way Distance (Meters)	Round-trip Delay (Nanoseconds)	One-way Distance (Meters)
Frequency and Timing	2.33	0.35	2.33	0.35
Receiver	2.67	0.40	2.67	0.40
Exciter and Transmitter	1.33	0.20	5.33	0.80
Microwave and Antenna	2.33	0.35	2.33	0.35
Tracking	0.67	0.10	0.67	0.10
Cables	1.33	0.20	1.33	0.20
Calibration	3.33	0.50	3.33	0.50
Reserve	3.33	0.50	12.47	1.87
Root Sum Square	6.6	1.0	14.7	2.2

Appendix A

1   H.W. Baugh, "Sequential Ranging - How It Works," JPL Publication 93-18, 6-15-1993

2   P. Kinman, "Two-Way Ranging With Filtered Squarewaves," Case Western Reserve University, 2-17-1995.